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Scientific Report #2

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ABSTRACT

Using the radiative transfer equations in the form given by Elsasser, R(u,T) tables needed to determine the atmospheric radiative flux in the 6.3 to 8.2 micron interval were computed. Values of constants, etc., used by Elsasser (1960) were used. Flux computations were made by a numerical integration of R(u,T) using the moisture and temperature distribution given by the radiosonde sounding of 29 April 1959 at Holloman Air Force Base, New Mexico. Comparisons were made with balloon measurements made by Strong at the same time and in the same spectrum interval. The computed net flux was found to agree with the measured flux within reasonable limits.

INTRODUCTION

Radiation charts, based on laboratory measurements and theoretical considerations, have been constructed by Mügge and Möller (1932), Möller (1943), Elsasser (1942, 1960), Yamamoto (1952), and others; and from atmospheric radiation measurements by Brooks (1941) and Robinson (1947).

The charts constructed theoretically are all based on one transform or another of the same fundamental equation of radiative transfer:

$$F = -\int_{0}^{\infty} d\nu \int_{u_0}^{u_1} B_\nu \frac{d}{du} \tau_f(uL)\, du \qquad (1)$$

where F is the radiative flux; ν is the wave number; B_ν is the wave number dependent black body flux; u is the absorbing path length; L is the absorption coefficient; and $\tau_f(uL)$ is the transmission function, expressed as a function of the absorbing path length u, and varying absorption coefficient L.

The solution of this equation cannot be found analytically since the relationship between temperature and path length is an empirical one, varying from one sounding to another. A graphical or numerical method of solution must be used. Mügge and Möller (1932) devised a method of graphical integration which they applied to equation (1). Möller (1943) used the same process. Elsasser (1942) used a similar method, but made a change in the form of the equation so that temperature, instead of the path length, was made the independent variable. The final form of the equation used by Elsasser (1942) was:

$$F = \int_{C} dT \int_{o}^{\infty} \frac{dB_\nu}{dT} \tau_f(uL)\, d\nu = \int_{C} Q(u,T)\, dT \qquad (2)$$

The closed path of integration C is defined by an existing atmospheric distribution of temperature and moisture. The integration was performed by the measurement of areas on a chart.

In his later work Elsasser (1960) has largely abandoned the graphical method of flux computations and has put increasing emphasis on numerical methods. He has defined a new quantity:

$$R(u,T) = \frac{dB}{dT} - Q(u,T) \tag{3}$$

which is a measure of the amount of energy absorbed rather than the amount emitted. To a great extent, he has been able to replace theoretically calculated transmission functions by laboratory measurements made in the early 1950's.

One of the problems foremost in the use of radiation charts is the question as to whether or not the charts in fact permit accurate calculation of radiation in the atmosphere. In order partially to check this question, at least insofar as the portion of the Elsasser (1960) chart within a narrow wave length interval is concerned, we chose to compare it with measurements made by Strong (1959). Inasmuch as Strong's interval of measurement (8.2μ to 6.3μ, i.e., 1220 cm^{-1} to about 1580 cm^{-1}) did not match Elsasser's interval for the 6.3μ band (1220 to 2280 cm^{-1}), we repeated Elsasser's chart calculation for Strong's interval (i.e., 1220 to 1580 cm^{-1}).

Thus, we have calculated an Elsasser type chart to match the Strong measurements, and for the purpose of checking Elsasser's method of calculation against Strong's measurements.

CALCULATION METHODS

The methods, equations, and constants used by Elsasser (1960) were used exclusively in our calculations. Only the limits of integration were changed. Simpson's rule for numerical integration and a subinterval of 20 cm^{-1} were used for all equations.

Transmission Functions.

No attempt was made to find transmission functions theoretically. The laboratory measurements of Daw (1956) were used as tabulated by Elsasser (1960).

For the purpose of this work, intermediate values of the Daw transmission functions were obtained by means of a second degree polynomial interpolation (Milne, 1949) to give values for each integration interval in ν. Logarithmic interpolation on u was used to determine the transmission functions for each one-tenth increment in $\log_{10} u$.

The beam transmission $\tau(uL)$ was changed to slab transmission $\tau_f(uL)$ by means of the relationship

$$\tau_f\ (\log uL) = \tau(\log uL + 0.20) \qquad (4)$$

as recommended by Elsasser.

Absorption Coefficients.

The transmission function τ_f is a function of L, the generalized absorption coefficient, as well as the path length u. This absorption coefficient is in turn a function of the temperature. In terms of change from a reference temperature T_o, Elsasser gives this temperature dependence to be:

$$\log L(T) = \log L(T_o) + \Delta \log L \qquad (5)$$

$\Delta \log L$ is given by:

$$\Delta \log L = -a \frac{T_o - T}{T_o} (\nu - \nu_o)^2 + \log \frac{T_o}{T} \qquad (6)$$

Equations (5) and (6) were evaluated using the same values of constants as published by Elsasser (1960).

Black Body Flux Change With Temperature.

The black body flux is given by Planck's law:

$$B = \frac{P\nu^3}{e^{q\nu/T}-1} \tag{7}$$

The derivative of this flux with respect to temperature is:

$$\frac{dB_\nu}{dT} = \frac{P}{q^3} \frac{T^2 x^4 e^x}{(e^x - 1)^2} \tag{8}$$

In this equation q = 1.4389 cm degree, p = 3.7412 erg cm^2/sec, and $x = q\nu/T$. Integrated values of $\frac{dB_\nu}{dT}$ over the interval were tabulated for every 10C temperature.

R(u,T) Values.

Values of

$$R(u,T) = \int \frac{dB_\nu}{dT} \left[1 - \tau_f(uL)\right] d\nu \tag{9}$$

were computed and tabulated for 10° increments in temperature from -80°C to 40°C and for two-tenths increments in $\log_{10} u$ from minus six to one.

Band Area Correction.

The band area correction factors A/A_1 obtained by Elsasser were assumed to have the same value for this portion of the 6.3μ band as they had for the entire 6.3μ band, for which they were originally computed. These correction factors were interpolated linearly for one-tenth increments in log u, and each R(u,T) was multiplied by the appropriate factor. Elsasser's values were modified slightly to make the R(u,T) values for small log u values more consistent.

Table 1. Band area correction factors.

	log u							
	-6	-5	-4	-3	-2	-1	0	+1
Elsasser	-	4.2	1.7	1.18	1	.94	1	1
Adopted	5	3	1.7	1.18	1	.94	1	1

Off Chart Areas.

The contribution to the radiative transfer for temperature of the absorbing medium from absolute zero to -80°C was computed by numerical integration using (8) and (9), and tabulated separately. Since the digital computer placed a restriction on the size of x in (8), the actual integration was performed from T = 49°K to 193°K. The error involved in assuming dB/dT equal to zero for temperatures from zero absolute to 49 degrees absolute was negligible since $e^x/(e^x - 1)^2$ for large x (i.e., small T) is extremely small.

The off chart areas were determined for each five-tenths increment in $\log_{10} u$.

Black Body Flux.

The black body flux over the interval

$$B = \int_{1220}^{1580} \frac{P\nu^3}{e^{q\nu/T} - 1} \qquad (10)$$

was computed and tabulated for every two degrees temperature from -80°C to 40°C.

RESULTS

Calculations of the net flux at various levels were made using the radiosonde sounding of 29 April 1959 at Holloman Air Force Base,

New Mexico with two different moisture distributions being assumed above 560 mb (16,000 ft). The radiosonde indicated motorboating above that level. In assumption 1 we assumed a linear decrease in relative humidity from 25% at 560 mb to 10% at 250 mb. Above 250 mb a constant mixing ratio of 0.02 g/kg was used. In assumption 2 a constant relative humidity of 5% was assumed above 560 mb. The resulting sounding data are given in Table 2.

The values obtained in this way were compared with the balloon measurements made by Strong (1959), in this spectrum interval at the same time the sounding was taken. The comparisons are shown in Table 3 and Figure 1. The computed net flux values agree with Strong's observed values as closely as could be expected with the method used. The 15,000 ft level (580 mb) shows the greatest discrepancy, approximately 5 w/m^2, or 25% of the measured values. At the next two higher levels (500 mb and 331 mb) the difference is approximately 2 w/m^2, or about 10% of the measured values. The higher levels in the dry air extrapolation (2) are within 1 w/m^2, or about 5% of the measured values.

The differences are believed due to the uncertainty of the assumed moisture distribution in the motorboating region. For example, it would seem that drifting atmospheric regions (or "clouds") of greater or less humidity during the Strong flight may be indicated by the Strong data, independent of our calculations.

CONCLUSION

Our results are uncertain to the degree influenced by the humidity extrapolation. On examination of the computed flux values under both assumptions, it is found that the higher flux values are associated with the assumed dryer atmosphere. These values also agree more closely with

Table 2. Radiosonde sounding for Holloman AFB, New Mexico.

29 April 1959 0900 GCT

Pressure (mb)	Temp. (°C)	q_1 g/kg	q_2 g/kg	Pressure (mb)	Temp. (°C)	q_1 g/kg	q_2 g/kg
873	12.5	2.568	2.568	150	-65.9	0.020*	0.001*
863	20.9	4.499	4.499	129	-67.6	0.020*	0.001*
850	20.5	4.669	4.669	126	-67.3	0.020*	0.001*
827	20.0	4.300	4.300	118	-66.8	0.020*	0.001*
700	9.0	3.231	3.231	101	-68.0	0.020*	0.001*
696	8.6	3.151	3.151	85	-64.9	0.020*	0.002*
580	-4.6	2.074	2.074	71	-66.0	0.020*	0.002*
560	-3.8	1.236	1.236	66	-65.4	0.020*	0.002*
500	-9.2	0.836*	0.193*	57	-60.9	0.020*	0.005*
488	-10.5	0.667*	0.175*	55	-62.5	0.020*	0.004*
400	-24.5	0.210*	0.066*	47	-60.2	0.020*	0.007*
331	-36.0	0.075*	0.028*	45	-57.1	0.020*	0.011*
300	-41.5	0.044*	0.017*	42	-57.8	0.020*	0.011*
282	-45.0	0.025*	0.012*	38	-53.9	0.020*	0.020*
250	-51.1	0.020*	0.004*	29	-56.5	0.020*	0.019*
235	-54.0	0.020*	0.003*	23	-49.6	0.020*	0.056*
200	-60.0	0.020*	0.002*	21	-51.1	0.020*	0.051*
170	-63.9	0.020*	0.001*	19	-49.8	0.020*	0.066*
161	-64.9	0.020*	0.001*				

*Estimated due to motorboating.

Table 3. Computed and measured flux (1220-1580 cm^{-1}) at various altitudes.

Altitude (ft)	Pressure (mb)	Computed F Up (w/m^2) Moist (1)	Computed F Down (w/m^2) Moist (1)	Computed F (w/m^2) Moist (1)	Computed F Up (w/m^2) Dry (2)	Computed F Down (w/m^2) Dry (2)	Computed F (w/m^2) Dry (2)	Measured F (w/m^2) Strong
15,000	580	26.7	11.9	14.8	26.7	11.1	15.6	20.3
19,000	500	24.6	8.1	16.5	24.8	6.0	18.8	20.6
29,000	331	20.2	1.5	18.7	21.7	1.1	20.6	22.7
35,000	250	19.4	0.7	18.7	20.9	0.2	20.7	20.3
43,000	172	18.9	0.3	18.6	20.7	0.2	20.5	20.7
49,000	126	18.8	0.3	18.5	20.7	0.2	20.5	21.1

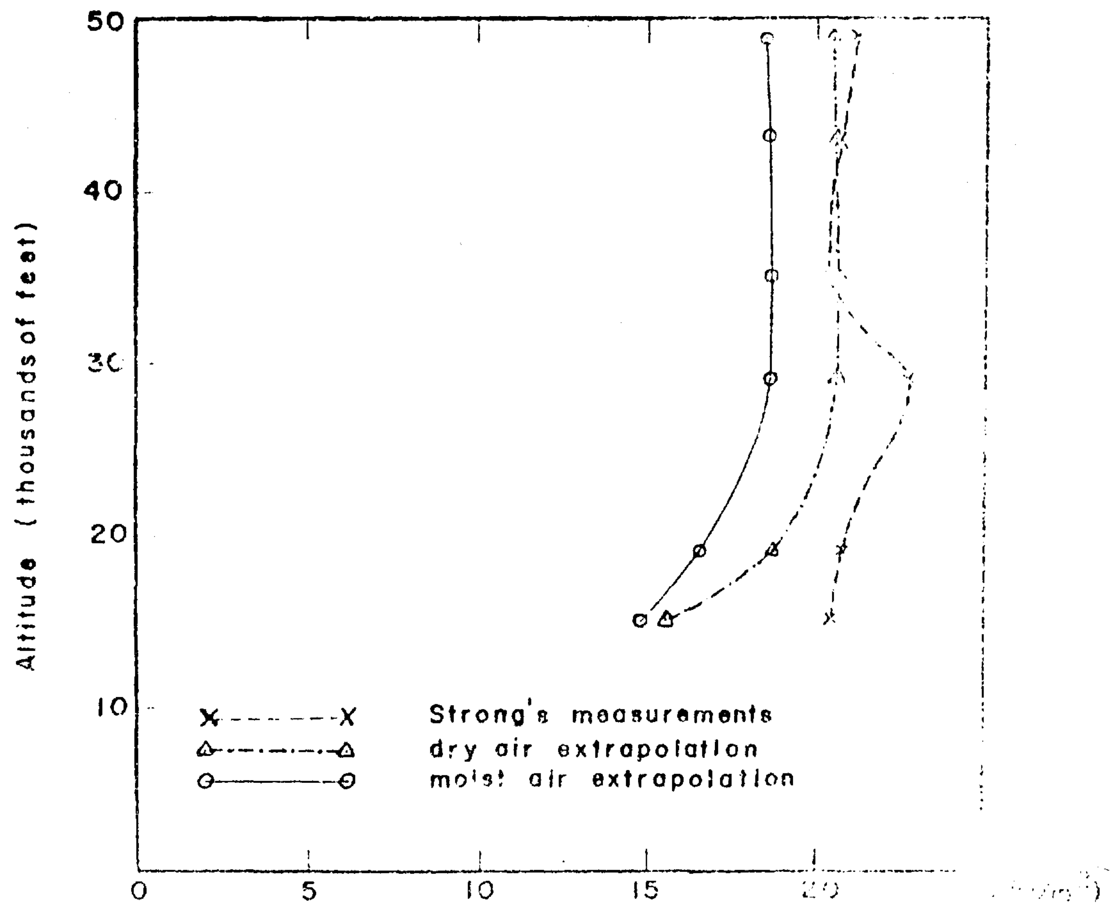

Figure 1. Comparison of measured and computed flux. (1220-1580 cm^{-1})

Strong's measurements. If trial and error estimates of different atmospheric humidity distributions were to be assumed for that part of the sounding above 560 mb, it is believed that the calculated flux values at most levels could be made as close to Strong's measured values as desired.

If the actual moisture distribution could have been measured accurately in the region of the atmosphere where the sounding was reported motorboating, it is our opinion that the computed values would have approximated Strong's measurements.

RECOMMENDATIONS

This investigation further demonstrates the need for more accurate measurements of humidity than are to be had from the standard radiosonde equipment, especially in regions where the moisture content of the atmosphere is so low that the present radiosonde indicates "motorboating".

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Explanation of Table 4

The tabulated values of R(u,T) are in Burroughs floating point notation, just as they were printed by the digital computer. Each ten digit number consists of a two digit "exponent" (50 + power of 10) and an eight digit decimal "significant figure", with the decimal point understood to the left of the first significant digit.

The following examples illustrate the reading of Burroughs floating point numbers:

1. 5127689543

   $51 - 50 = 1,\ 10^{1} \times .27689543 = \underline{2.7689543}$

2. 4987543129

   $49 - 50 = -1,\ 10^{-1} \times .87543129 = \underline{0.087543129}$

Table 4. R(u,T) in watts/meter^{2} for 6.3μ to 8.2μ .

	log(uL)	+0.0	+0.2	+0.4	+0.6	+0.8
T = -80C	-6	4727493081	4751738533	4780879457	4812466651	4816878723
	-5	4821556610	4828602175	4833545947	4838996540	4845274412
	-4	4853481231	4864621437	4874375018	4885367008	4897619137
	-3	4911221359	4913261243	4914952202	4916734562	4918913642
	-2	4920883785	4923205795	4925472909	4927458487	4929676545
	-1	4932527693	4935205127	4938097893	4940957538	4943723357
	0	4946106120	4948406665	4950564589	4952626984	4954551991
		5319300000	T = -80°C			
T = -70C	-6	4741569416	4779026747	4812379958	4819128141	4826231722
	-5	4833450419	4844275983	4852219985	4860589890	4870589632
	-4	4882973024	4910012313	4911568667	4913220354	4915175044
	-3	4917404048	4920557914	4923260610	4925965942	4929431930
	-2	4932336433	4936000173	4939530826	4942431358	4945914608
	-1	4950106501	4954282819	4958600743	4962852408	4967179285
	0	4970543744	4974129804	4977119148	4980037527	4983138621
		5320300000	T = -70°C			
T = -60C	-6	4762589593	4811893683	4818621879	4828744679	4839376511
	-5	4850142774	4866315105	4878091839	4890576475	4910537060
	-4	4912377053	4914980202	4917306420	4919761423	4922642607
	-3	4925988763	4930575828	4934603500	4938612907	4943666357
	-2	4948061467	4953298574	4958607268	4962785922	4967739404
	-1	4974001668	4979615118	4986161120	4992228860	4998128725
	0	5010306671	5010760392	5011219248	5011595864	5012032055
		5321300000	T = -60°C			

Table 4. (Cont'd)

R(u,T) in watts/meter^2 for 6.3 μ to 8.2 μ .

	log(uL)	+0.0	+0.2	+0.4	+0.6	+0.8
T = -50C	-6	4771819821	4814524251	4824967577	4838754658	4855045508
	-5	4869705096	4891831997	4910952691	4912630252	4914845378
	-4	4917342966	4920891574	4924400072	4927741981	4932111911
	-3	4936748783	4943091066	4949160252	4954792215	4962098980
	-2	4968302858	4975663783	4983127525	4989123519	4995899484
	-1	5010472780	5011267297	5012154170	5013038024	5013804808
	0	5014498053	5015149474	5015697634	5016258719	5016774867
		5322300000	T = -50°C			
T = -40C	-6	4789232258	4818690413	4832002631	4850019127	4873763558
	-5	4893874030	4912323977	4914975485	4917322475	4920637534
	-4	4923752159	4928651527	4933781707	4938087757	4944774810
	-3	4950807801	4959385338	4968442851	4975944402	4987053060
	-2	4995046748	5010521951	5011610306	5012391795	5013412684
	-1	5014529974	5015588536	5016831058	5017951228	5018987715
	0	5019928743	5020692731	5021386593	5022193964	5022808802
		5323300000	T = -40°C			
T = -30C	-6	4812059361	4825256445	4843221236	4867506665	4899515389
	-5	4912655009	4916594549	4920149683	4923307237	4927745576
	-4	4931927296	4938522087	4945418282	4951121624	4960118752
	-3	4968120205	4979589255	4991806225	5010162861	5011662834
	-2	5012723291	5014073593	5015528968	5016532941	5017877714
	-1	5019351950	5020736793	5022398425	5023825244	5025147388
	0	5026420759	5027387000	5028247348	5029323827	5030013611
		5324300000	T = -30°C			

Table 4. (Cont 'd)

R(u,T) in watts/meter^2 for 6.3μ to 8.2μ .

	log(uL)	+0.0	+0.2	+0.4	+0.6	+0.8
T = -20C	-6	4815863626	4833220495	4856894479	4888797306	4913084751
	-5	4916649509	4921814437	4926493733	4930638895	4936463166
	-4	4941987589	4950706952	4959679597	4967190578	4979137267
	-3	4989339265	5010457506	5012058508	5013316736	5015328837
	-2	5016672437	5018436903	5020351883	5021606648	5023413991
	-1	5025241678	5027014006	5029256692	5030929835	5032684329
	0	5034291746	5035312362	5036662126	5037795876	5038594255
		5325300000	T = -20°C			
T = -10C	-6	4820377433	4842669046	4873040951	4911393448	4916783824
	-5	4921329445	4927917947	4934104599	4939472106	4946987189
	-4	4953955598	4965237854	4976483788	4986327407	5010183235
	-3	5011461328	5013448201	5015486333	5017096896	5019740792
	-2	5021371997	5023664610	5026075242	5027620763	5030067931
	-1	5032193238	5034511325	5037372382	5039236972	5041666058
	0	5043487707	5044677844	5046466878	5047562052	5048750377
		5326300000	T = -10°C			
T = OC	-6	4825630140	4853663362	4891820843	4914315691	4921082912
	-5	4926782597	4935025764	4942782288	4949482796	4958868274
	-4	4967871217	4982129511	4996003450	5010849733	5012813004
	-3	5014369927	5016884913	5019390025	5021453073	5024823522
	-2	5026747912	5029694313	5032611550	5034553035	5037749695
	-1	5040119249	5043150277	5046537525	5048794387	5052040364
	0	5053785248	5055380813	5057623317	5058741021	5060428874
		5327300000	T = 0°C			

Table 4. (Cont'd)

R(u,T) in watts/meter^2 for 6.3μ to 8.2μ.

	log(uL)	+0.0	+0.2	+0.4	+0.6	+0.8
T = 10C	-6	4831638977	4866239334	4911329401	4917655516	4925995137
	-5	4932987481	4943103980	4952630632	4960823710	4972307875
	-4	4983361697	5010083411	5011797358	5013337672	5015755581
	-3	5017666480	5020777455	5023817413	5026387175	5030577361
	-2	5032822715	5036505847	5039947550	5042412204	5046470077
	-1	5049131131	5053038388	5056842742	5059803157	5064124483
	0	5065598318	5067864846	5070063398	5071631782	5074095876
		5328300000	T = 10°C			
T = 20C	-6	4838409461	4880408348	4913747866	4921415536	4931524151
	-5	4939964492	4952180218	4963665415	4973514618	4987330788
	-4	5010061912	5012163387	5014223991	5016072993	5018977142
	-3	5021268405	5024999784	5028640904	5031710787	5036719373
	-.	5039389617	5043775991	5047855691	5050770866	5055574108
	-.	5058703503	5063322562	5067788042	5071284721	5076383031
	0	5078071342	5080743981	5083269174	5085123936	5088036239
		5329300000	T = 20°C			

Table 4. (Cont'd)

R(u,T) in watts/meter^2 for 6.3 μ to 8.2 μ.

	Log(uL)	+0.0	+0.2	+0.4	+0.6	+0.8
T = 30C	-6	4845936212	4896159004	4916435422	4925592358	4937664824
	-5	4947706229	4962243887	4975892163	4987565395	5010395196
	-4	5011970187	5014462069	5016904768	5019093452	5022533139
	-3	5025242566	5029656272	5033957574	5037575709	5043478791
	-2	5046616412	5051772326	5056543329	5059948947	5065538130
	-1	5069196858	5074591874	5079763403	5083846277	5089726963
	0	5091700106	5094821717	5097675927	5099850998	5110306164
		5330300000	T = 30°C			
T = 40C	-6	4854204012	4911345936	4919386532	4930177210	4944404122
	-5	4956195466	4973271778	4989326041	5010300313	5012226211
	-4	5014075842	5017003163	5019897556	5022485890	5026523829
	-3	5029747272	5034989313	5039988432	5044325556	5051103034
	-2	5054897387	5061094320	5066467357	5070672657	5076893219
	-1	5081456526	5088155687	5093613048	5098860899	5110491097
	0	5110764335	5111182961	5111416942	5111724247	5111923521
		5331300000	T = 40°C			

Table 5. Black Body Flux in watts/meter^2 over the interval 6.3μ to 8.2μ.

	0.0	2.0	4.0	6.0	8.0
30°C	49.328	51.485	53.709	55.998	58.353
20°C	39.483	41.329	43.236	45.204	47.235
10°C	31.149	32.680	34.296	35.967	37.696
0°C	24.115	25.414	26.763	28.163	29.615
- 0°C	24.115	22.865	21.664	20.509	19.400
-10°C	18.336	17.315	16.338	15.401	14.506
-20°C	13.650	12.832	12.051	11.307	10.596
-30°C	9.923	9.281	8.671	8.092	7.543
-40°C	7.023	6.531	6.066	5.627	5.213
-50°C	4.823	4.456	4.111	3.787	3.484
-60°C	3.200	2.934	2.687	2.456	2.241
-70°C	2.041	1.856	1.684	1.525	1.379
-80°C	1.244				

Table 6. Rate of change of black body flux with temperature.

$\int \frac{dB_\nu}{dT} \, d\nu$ watts/meter^2

-80°	.0664
-70°	.0968
-60°	.1367
-50°	.1884
-40°	.2419
-30°	.3278
-20°	.4177
-10°	.5189
0°	.6344
10°	.7631
20°	.9044
30°	1.058
40°	1.224

Table 7. Off chart areas watts/meter^2.

$\int_0^{193^\circ K} R(u,T)\,dT$

Log u	
-6	.0052
-6+.5	.0186
-5	.0390
-5+.5	.0649
-4	.1059
-4+.5	.1617
-3	.2451
-3+.5	.3516
-2	.4822
-2+.5	.6287
-1	.8076
-1+.5	.9796
0	1.113
+.5	1.127